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Passive control of shock oscillation around a biconvex circular arc airfoil in a channel

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Abstract

A strong normal shock wave, generated on an airfoil, is responsible not only for limiting the aerodynamic performance but also for shock induced boundary layer separation. This shock induced boundary layer separation results aerodynamics instabilities (buffet), high cycle fatigue failure (HCF), nonsynchronous vibration (NSV), flutter and so on. In the present study, a numerical computation has been performed to control the unsteady shock oscillation over a 12% biconvex circular arc airfoil in a two dimensional channel. Reynolds averaged Navier-Stokes (RANS) equations with k-ω shear stress transport (SST) two equation turbulence model has been applied for computational analysis. To control the shock oscillation over a biconvex circular arc airfoil (referred as base airfoil), the geometry of the base airfoil has been modified by incorporating a cavity with two openings on both upper and lower surface of the airfoil. The cavity has been incorporated in such a manner that the mean position (along chord length) of the cavity is placed where the RMS of static pressure fluctuation on airfoil surface (for base airfoil) is maximum. The length and depth of the cavities are kept 10% and 2% of the chord length, respectively. The behavior of the shock wave oscillation has been studied for a particular pressure ratio (defined as the ratio of back pressure to inlet total pressure) of 0.69. The present study investigates the shock wave characteristics over (a) airfoil with no cavity (base airfoil) and (b) airfoil with cavity with 60% opening (60% of cavity length is open). The results showed that the incorporation of cavities on airfoil surfaces not only affect the flow field but also change the behaviour in a great extent. For pressure ratio 0.69, the flow field becomes steady for airfoil with cavities while for base airfoil the flow field was unsteady. The results also show that incorporation of a cavity on airfoil surfaces changes the type of shock wave from normal to λ shock wave.

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Keywords: shock wave; shock induced separation; passive control; unsteady shock oscilation.

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1. Introduction

Transonic flow over an airfoil has revealed itself as a very important research area for the last few decades due to its versatile use in practical life such as compressor blades, turbine cascades, aircraft wings and so on. The flow field for transonic flow over an airfoil shows different characteristics depending on various parameters like pressure ratio (ratio of back pressure to inlet total pressure), airfoil geometry, fluid properties and etc. For such flow a shock wave is generated on the airfoil surfaces due to sudden increase of pressure. In some cases this shock wave starts to oscillate and make the flow unsteady. This unsteady shock oscillation results in increasing drag and power requirement to operate the Machines. Thus scientists and engineers are putting their concerned effort to control this unsteady shock oscillation to minimize the drag and power requirement. The passive control technique by modifying the airfoil geometry was demonstrated experimentally by Bahi et al. [1] in 1983. In 1984, Nagamatsu et al. [2] showed that drag on an airfoil can be reduced by implementing a porous cavity in the region of shock wave. The encouraging results have led to many experimental and analytical investigations that have been summarized fairly by Raghunathan [3] in 1989. In 1993, Mc Kormick [4] showed that the passive cavity substantially reduce the total pressure loss through the shock wave through more isentropic compression, though the viscous loss in downstream of the shock increases significantly.

In 2010, Doerffer et al. [5] investigated the effect of porous cavity on reduction of high speed impulsive (HSI) noise on helicopter blades. This investigation also mentions that porous cavity can reduce the pressure fluctuation over the airfoil. In 2014, Hamid et al. [6] investigated the compressible flow around a biconvex circular arc airfoil (12% thick) in a channel. The investigation shows that the flow over an airfoil changes its type, nature and characteristics with change in pressure ratio. In the present investigation, the geometry of the airfoil of reference [6] has been modified to control the unsteady shock oscillation at pressure ratio 0.69.

Nomenclature

c	Chord length of airfoil
c_p	Coefficient of pressure
x, y	Position co ordinates
M_s	Shock Mach number
x_s	Shock position
t	Time
T	Time period of shock oscillation
q_0	Free stream dynamic pressure
P_{rms}	RMS pressure fluctuation
PR	Pressure ratio

2. Airfoil Geometry and Computational Domain

The base airfoil is identical as reference [6], which is a 12% thick biconvex circular arc airfoil with chord length of 48 mm. In order to control the shock wave the geometry of the airfoil is modified by incorporating two porous cavities on both upper and lower surface of the airfoil. The length and depth of the cavities are kept 10% and 2% of the chord length respectively. The two edges of the modified airfoil are kept sharp like the base airfoil.

The computational domain is discretized by structured mesh with 121524 grids which provides grid independent solution (shown in figure 1,a; 1,b; 1,c). The average wall y^+ value is 0.8 and the distribution along the airfoil surface is shown in figure 2.

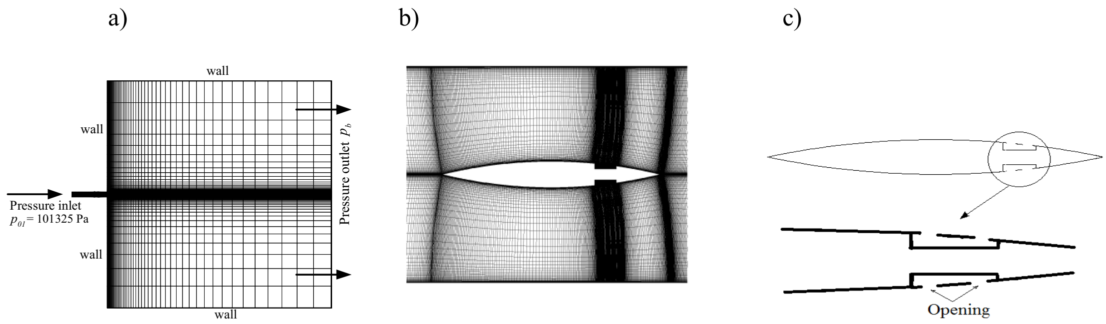


Fig. 1. (a) Computational domain; (b) Close view of mesh network; (c) Airfoil with cavity

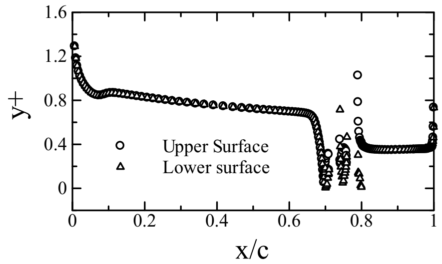


Fig. 2. y^+ distribution on airfoil surfaces

3. Numerical Method and Boundary Conditions

The flow field was considered to be viscous, compressible, turbulent, and unsteady. Governing equations for present RANS computation are the conservation of mass, conservation of momentum and energy equations written in 2-D coordinate system. Turbulence is modeled by additional two equation of *k-ω* SST (Shear Stress Transport). The governing equations are discretized spatially using finite volume method of second order scheme. A time step size 10^{-6} is used for unsteady computation. The flowing fluid (air) was assumed to be ideal gas. The viscosity is considered to vary according to Sutherland's Law.

No-slip and adiabatic wall condition is applied at all solid boundaries. The inlet and outlet are conditioned as pressure inlet and pressure outlet respectively. The pressure at both inlet and outlet are constant and are 101,325 Pa and 70,000 Pa respectively, which gives a pressure ratio of 0.69.

4. Results and Discussion

In reference [5], Hamid et al. studied the flow over a simple biconvex circular arc airfoil (base airfoil) at different pressure ratio. For pressure ratio 0.69, the flow field was unsteady and supersonic with an oscillating shock wave on both upper and lower surface of the airfoil. The frequency of the unsteady shock oscillation was 865 Hz with oscillation time period of 1.15×10^{-3} seconds. The oscillatory motion is clearly understood from the sequential contour maps as shown in figure 3. From figure 3, it is seen that the shock wave is normal type and its movement is continuous on both upper and lower surfaces, which corresponds to Tijdaman type 'A' shock movement.

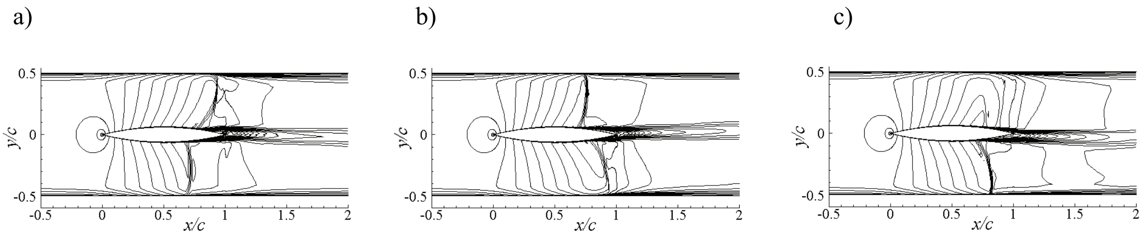


Fig. 3. Sequential contour maps for base airfoil, (a) t/T=0; (b) t/T=3/8; (c) t/T=6/8.

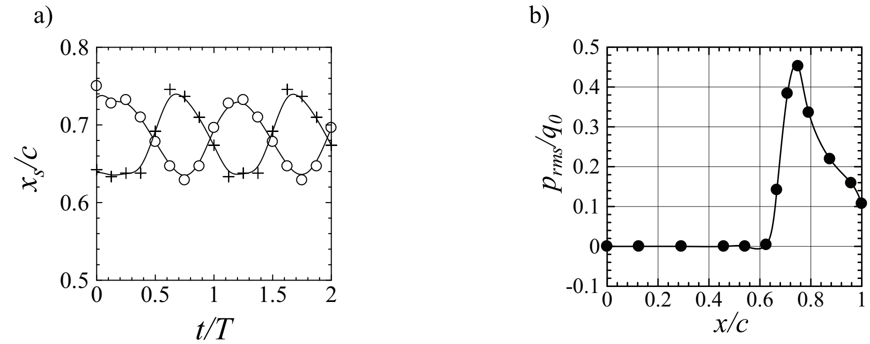


Fig. 4. (a) Shock oscillation over base airfoil at PR=0.69; (b) RMS pressure fluctuation over base airfoil at PR=0.69.

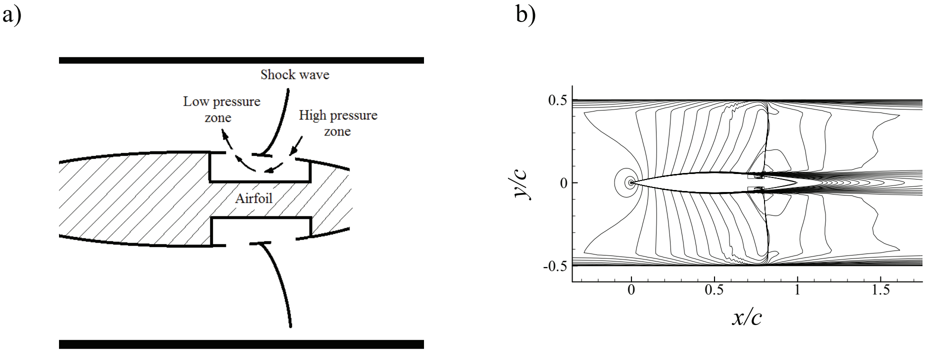
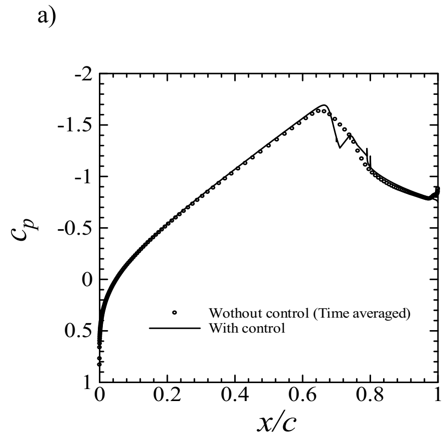


Fig. 5. (a) Mechanism of air flowing from downstream to upstream; (b) Mach contour with passive control

The movement of the shockwave is more clearly understood when shock position is plotted against time (figure 4,a). In this figure the line with circle and line with cross represents shock position on upper and lower surface respectively. Here it is evident that the shock used to move within the range of x/c=0.64 to x/c=0.75 for both upper and lower surface with a maximum pressure fluctuation at x/c=0.75 (shown in figure 4,b).

In order to control the shock oscillation, two cavities with length and depth of 0.1c and 0.02c respectively has been placed on both upper and lower surface of the airfoil. The mean position of the cavities are at x/c=0.75, where the pressure fluctuation for base airfoil was maximum. The cavities are rectangular in shape and covered with porous plates (shown in figure 1,c). The porosity ratio of the cavity is then defined as the ratio of open length to total cavity length. This study investigates the effect of porous cavity on shock movement for porosity ratio 60%.

After incorporating the cavities, some significant changes have been observed in the flow pattern and shock characteristics. The flow becomes steady with the passive control while the flow was unsteady without the control technique. That means there are no pressure fluctuation with time and no unsteady shock oscillation. Surely



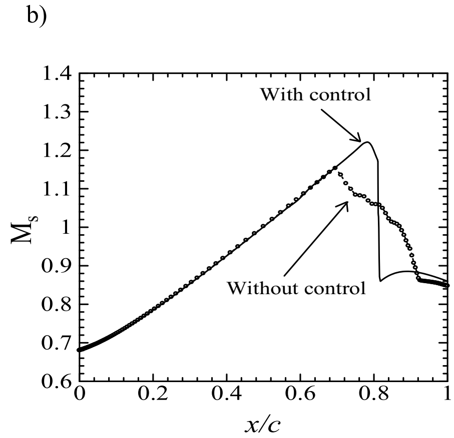


Fig. 6. (a) Distribution of pressure coefficient; (b) Distribution of Mach number

incorporating the porous cavity reduces the shock induced boundary layer separation which plays the main role in controlling the unsteady shock oscillation.

Levy [7] and Yamamoto and Tanida [8] tried to explain the mechanism that creates the self-sustained shock oscillation around airfoil in transonic flows. It was showed that the shock induced boundary layer separation leads toward the generation of a pressure wave by interacting with the trailing edge flow (wake flow). This pressure wave moves toward the leading edge, interact with the shock wave and provide the required energy to oscillate. So it is the prime objective of researchers to minimize the shock induced boundary layer separation. The porous cavity with 2 openings reduces the shock induced boundary layer separation by blowing air from downstream to upstream through the cavity. This flow of air (blowing) occurs due to the pressure difference across the shockwave. This phenomenon is illustrated in figure 5 (a). The blowing of air from downstream to upstream is felt by the main stream as a ramp (or a bump) leading to a generation of a front oblique shock wave which intersects the main shock creating a large λ-foot structure (shown in figure 5,b).

Figure 6 (a) shows the pressure coefficient distribution over the airfoil surface both with and without control technique. From this plot it is clear that the compression process across the shock wave for base airfoil has been replaced by series of several smaller compression processes. These multistage compressions with more isentropic processes reduce the total pressure loss [4].

From the Distribution of Mach number, along the line parallel to airfoil chord and placed at 0.25c distance vertically (figure 6,b), it can be concluded that the maximum shock Mach number has been increased after using the control technique. But For base airfoil the maximum shock Mach number (M_s), which is independent of position, varies ranging from 1.24 to 1.3 while with current passive control it reduces to 1.23. These two results may seem to be contradictory to each other but they are not. This contradiction is due to the actual mechanism behind controlling the shock oscillation. Without any control the maximum Mach number was created at different coordinates at different times, making the flow unsteady. But after incorporating the control system, the flow creates maximum Mach number at some particular region (far from airfoil surface) making the flow independent of time, thus a steady flow field is generated. Of course this process makes the shock wave stronger at some region, but in doing so it reduces the shock strength at the nearest region of the airfoil (shock foot). This decrease in shock strength at the foot reduces the shock induced boundary layer separation, yielding a steady flow field.

5. Conclusion

Modifying the airfoil geometry by porous cavity has been applied as a shock controlling technique and further effects has been analyzed in this study. The conclusion of this study can be summarized as below:

a) Porous cavity changes the transonic low characteristics around an airfoil by making the flow steady, which was unsteady before incorporating any control technique (base airfoil).
b) Use of porous cavity reduces the shock induced boundary layer separation by blowing air from downstream to upstream of the shock wave through the cavity hole.
c) This technique breaks down the long compression process across the shock into several more isentropic compression processes.
d) Though the technique makes shock wave stronger at some particular region, it weakens the shock wave at the shock foot and turned the shock into combined λ shaped shock wave.

From the present study it is evident that use of porous cavity can change the entire flow characteristics and shock properties. Thus it can be used as an effective passive control technique to overcome the detrimental effects of unsteady shock oscillation in case of transonic flows around airfoil

Acknowledgements

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